# PROPERTIES OF NON-UNIFORM ELECTRIC FIELDS THAT CONTRIBUTE TO PARTIAL DISCHARGES

A Thesis

Presented in Partial Fulfillment of the Requirements for

The Designation of Distinction for the

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## Abstract

Partial discharges (PD) can generally be described as electrical insulation breakdown that does not fully penetrate the insulating medium between two conductors. These electrical discharges commonly occur in small voids within an insulator or at the interface between insulators. Over time, PD can degrade and damage important insulation surrounding high voltage wiring or other equipment. The primary goal of this research project is to assist the current low-pressure partial discharge detection research conducted at The Ohio State University's high voltage laboratory. The results contained herein are divided into three main parts. First, electromagnetic field simulation software has been used to identify electric field patterns that are likely to produce PD. Qualitative comparisons were made between the computer simulation software's electric field strength graphs and the corresponding location of partial discharge formation found in the laboratory's low pressure test chamber. Furthermore, the second part compares the two detection devices (an oscilloscope and specialized PD detection computer) used in the high voltage laboratory based upon PD inception voltage to ensure consistency in laboratory measurements. Finally, the PD inception voltage values measured over a wide range of pressures within the test chamber and were compared with established data points from other PD research.

## Acknowledgments

I would like to thank my adviser, Prof. Donald Kasten, for giving me the opportunity to conduct an undergraduate thesis project.  His guidance and open nature to my suggestions has been great.  I have learned a great deal about practical lab research from him.

I also want to thank Prof. Stephen Sebo and Carol Liu for attending my thesis defense presentation and helping me schedule some of my lab tests. Further thanks to Carol for helping me with a morning's worth of testing.

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May 1, 1983……………………….Born – Covington, OH USA

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## Publications

1. R. Otte, “Properties of Electric Fields that Contribute to Partial Discharges.” *Denman Undergraduate Research Forum Poster Entry (in progress).* (2006).

## Fields of Study

Major Field: Electrical Engineering

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## List of Abbreviations/Nomenclature

PD……………………………………………Partial Discharge

FEA/FEM………………………………….....Finite Element Analysis/Method

Maxwell……………………………………....Electromagnetic field solver program published by Ansoft Corporation

HV Lab……………………………………….OSU's high voltage laboratory

Test Chamber………………………………OSU's pressure-controlled chamber capable of 0.1 to 760 Torr of pressure

# Chapter 1

## (1) Introduction

The partial discharge is a phenomenon that is well documented in high voltage engineering literature and literature on the physics of ionized gases [1, 2, 3, 4]. High voltage electrodes or other equipment can create large magnitude electric field strength areas that tend to excite the atoms or molecules of surrounding materials and ionize the electrons. The ionized electrons gaining/losing energy while changing states are what bring about partial discharges and the physical properties seen and observed from them. Some documented properties include:

" (a) Pulses in the electric circuit providing the voltage.
(b) Power loss in the dielectric
(c) Electromagnetic radiation, in the UV and visible bands.
(d) Sound radiation.
(e) Changes in gas pressure.
(f) Chemical changes in the material subjected to the discharges [2]. "

The primary goal of this research project is to determine the properties or conditions within *electric fields* that cause the onset of partial discharges. A low pressure test chamber available in OSU's high voltage laboratory was used to determine the location of partial discharges and the voltage at which they begin to appear continuously (inception voltage) for various experimental insulation configurations within the chamber. Figure 1 shows the primary parts of the chamber including the source of gas (cylinder), the high voltage AC connection, the adjustment valves for pressure control, and the actual test chamber itself.

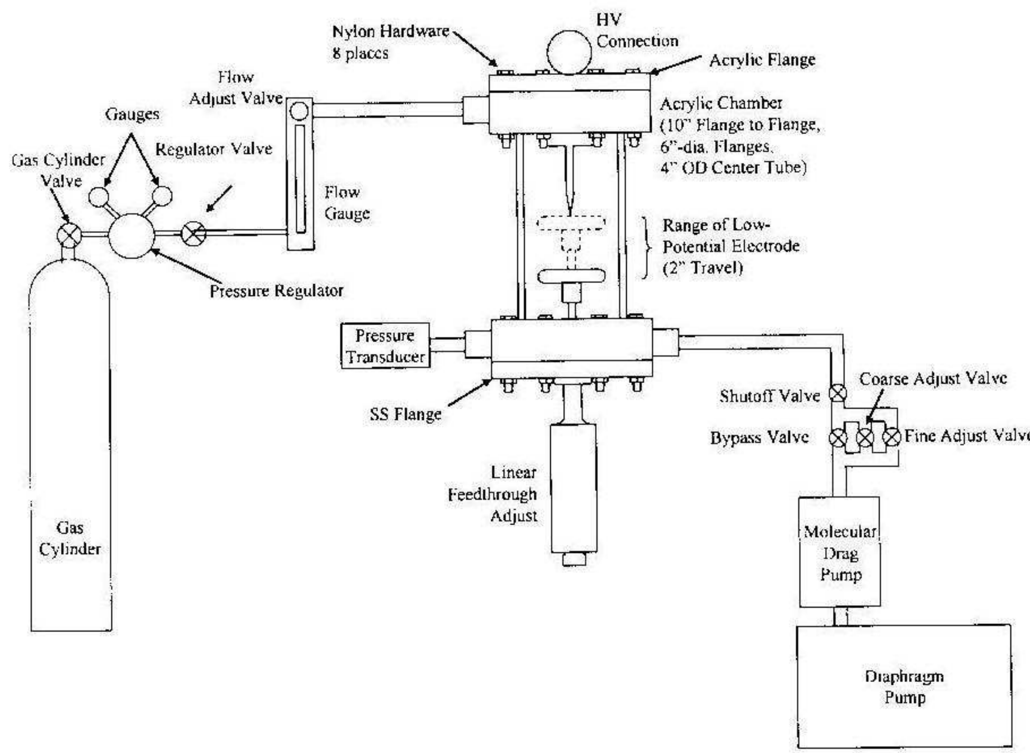


**Figure 1: High voltage laboratory pressure chamber [5].**

To achieve the primary goal just described, the following tests and analyses were performed and the results presented in chapters as follows.

Chapter 2 explains the process by which electromagnetic field simulation software was used to model the electric field surrounding each of the configurations in an attempt to identify patterns or disturbances in the electric field that correspond with areas of partial discharge development and so help predict where PD would occur in the experiment. Furthermore, the ability to predict with accuracy where PD occurs in a computer simulation was believed to also aid in the design of PD experiments that can successfully isolate and measure partial discharges.

Chapter 3 is a review over the PD detection equipment used to detect the onset of PD. In order to have some idea of the accuracy and compatibility between the two systems, a sample set of partial discharge onset data was collected and is analyzed here.

Chapter 4 presents the PD onset data collected for all experimental configurations.

### 1.1) Significance of the Problem

Partial discharges can be problematic in many high voltage engineering applications. Partial discharges commonly occur in small voids between a conductor and its surrounding insulation or within the insulation itself, and over time PD can degrade or permanently damage the insulation. The damaged electrical insulation can then pose a serious safety threat in some high voltage systems (short circuits, fires, shock hazards, etc). Thus, detecting partial discharges before insulation damage can occur is important for some sensitive systems.

Although partial discharge detection instruments are fairly well established for land-based systems, PD detection at higher altitudes is not as well-known. Thus, for electrical systems that operate in low pressure, high altitude environments (such as the electrical systems in aircraft and spacecraft) low pressure partial discharge detection can help improve safety and prevent system failures.

### 1.2) Research Background

The proposed research has accompanied ongoing low pressure partial discharge detection research at The Ohio State University's high voltage laboratory. The PD research at Ohio State is supported by an Air Force Research Laboratory (Dayton, OH) effort to develop a partial discharge detection system for the electrical wiring used inside spacecraft or high-altitude aircraft. A company called Innovative Scientific Solutions Inc. (Dayton, OH) is a contractor within the PD detection system development effort and Professors Kasten, Sebo and the resources at the OSU high voltage labs are part of a subcontracting arrangement.

The proposed research can help OSU's research goals by helping identify PD onset in the high voltage laboratory experiments. Also, the proposed research project will help show where PD is likely to occur in experiments and possibly aid in the design of experiments that can successfully isolate partial discharges for measurement and study.

### 1.3) Rationale Behind Research Approach

Since it is difficult to accurately measure or analyze the entire local electric field surrounding a high voltage experiment, a more viable option is to use a computer simulation software package to render a theoretical picture of the field. Most electromagnetic field simulation packages offered today have many useful features such as multiple electric field graphing modes, user-friendly modeling interfaces, and large libraries of materials available for use within models. While these features can develop a somewhat accurate model, laboratory experiments are still required to corroborate with any findings in computer simulations.

## 1.4) Equipment Used

*Electric Field Simulation Software*

The specific software used in this research was “Maxwell 2D Student Version” by Ansoft Corporation, a free version of the “Maxwell 2D/3D” line of products from Ansoft. “Maxwell 2D Student Version” will be simply referred to as Maxwell from this point forward, since it was the only product of that particular line that was used in this research. Maxwell utilizes a numerical method called the *finite element method* (also known as *finite element analysis*) to solve the basic electromagnetic equations for a very large amount of areas (elements) in a given simulation space. Two other numerical methods can be utilized by software to solve the same equations, namely the finite difference and boundary element methods, but as [6] indicates “… the finite element method incorporates most of the advantages of the other two techniques without incurring significant disadvantages.” The fact that Maxwell uses FEM along with many other powerful features associated with top of the line simulation software seemed to make it a natural choice for a software package to use for this research project’s purposes.

*Partial Discharge Detection Computer*

The PD detection computer is a beta-version of a PD detection device developed by Innovative Scientific Solutions, Inc. and was provided to OSU's high voltage lab for furthering research in low pressure PD detection and testing the software. It is a one piece package that is meant to be portable for ease of use to test equipment in the field. The operating software includes specific functions for analyzing PD incidents, including a plot indicating the number of partial discharges per second.

*Oscilloscope*

The oscilloscope used for PD detection in the high voltage lab is an HP digital oscilloscope with signal processing features. This piece of equipment was used for this research as a comparison to the PD detection computer for determining partial discharge current waveforms.

## 1.4) Experiments Performed

Three experimental configurations in the test chamber were used during the course of this research project. See Figure 2 for a Maxwell schematic drawing of each one. These schematics only show one half of their profile. Maxwell treats this half-profile as a symmetrical revolution about the central vertical axis. Each experimental configuration in the laboratory was vertically symmetrical, so this Maxwell schematic style represents each experiment accurately.

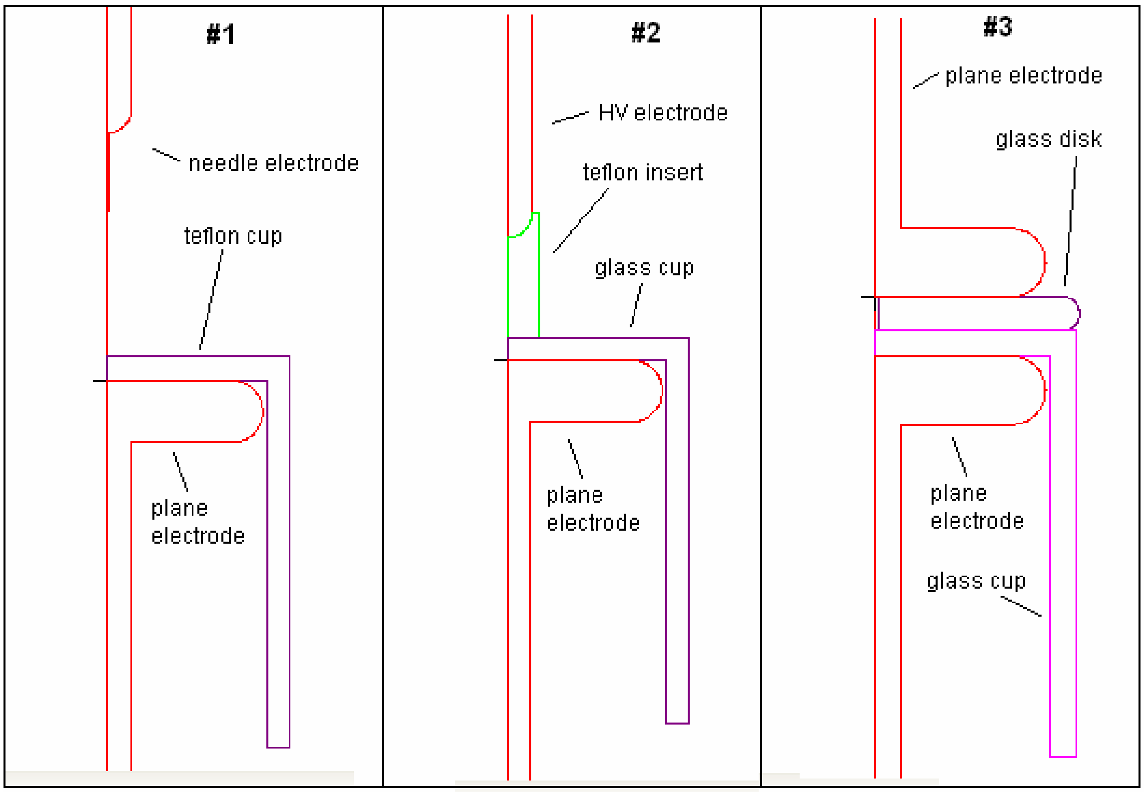


**Figure 2: Experimental configurations.**

The first pane in Figure 2 shows Experiment #1 (also referred to as "needle-plane" experiment). The second pane illustrates Experiment #2 (also referred to as the "Teflon insert" configuration). Finally, Experiment #3 illustrates the "glass disk" experimental setup. Each configuration exhibits a different high voltage (top) electrode, but each exhibits the same lower electrode and some form of barrier (cup) that prevents any sparkover between the electrodes.

# Chapter 2

# (2) Partial Discharge Location Using Computer Simulation

## 2.1) Methodology

The first stage in the research was to simulate controlled experiments expected to be conducted in the high voltage laboratory's low pressure test chamber. The primary hypothesis behind doing so was that an electromagnetic field simulation software package could be used to accurately produce a rendition of the electric field surrounding the experimental configuration and from that information predict the location of PD during the experiment. The primary Maxwell graph of interest was the electric field strength magnitude graph. After processing a solution, Maxwell can produce a shaded scale that indicates an electric field strength range in volts per meter throughout the entire schematic.

For all simulations, a HV electrode voltage of 10 kV was chosen simply as an arbitrary basis for comparing all subsequent simulations. The graphs of electric field strength are then judged on *relative* magnitude within the experimental setup. To predict possible areas of PD development, it stands to reason that areas associated with very high magnitude electric field strength in the simulations would be the first areas to see ionization of the air within an enclosed laboratory test

## 2.2) Results

Figure 3 below shows the continuously visible partial discharge glow for several different pressures in the high voltage chamber for an experiment consisting of a rounded high voltage electrode that fits snugly in a white Teflon barrier insert (#2). Furthermore a glass cup barrier fits over the bottom flat electrode. Before viewing the results, it was predicted that the partial discharges would congregate at the bottom of the rounded electrode and along the side of the Teflon piece. Viewing Figure 4, we see a relatively high magnitude electric field strength especially at the tip of the top electrode and along the Teflon-air interface (circled portions). According to [7] surface discharges at the interface between the top electrode and the Teflon insert and the Teflon-air interface are expected when high electric field strength is present. Thus it appears that using Maxwell in conjunction with some knowledge of the behavior of electric fields at the interfaces between different media, one can successfully identify the location of PD for this particular experiment.

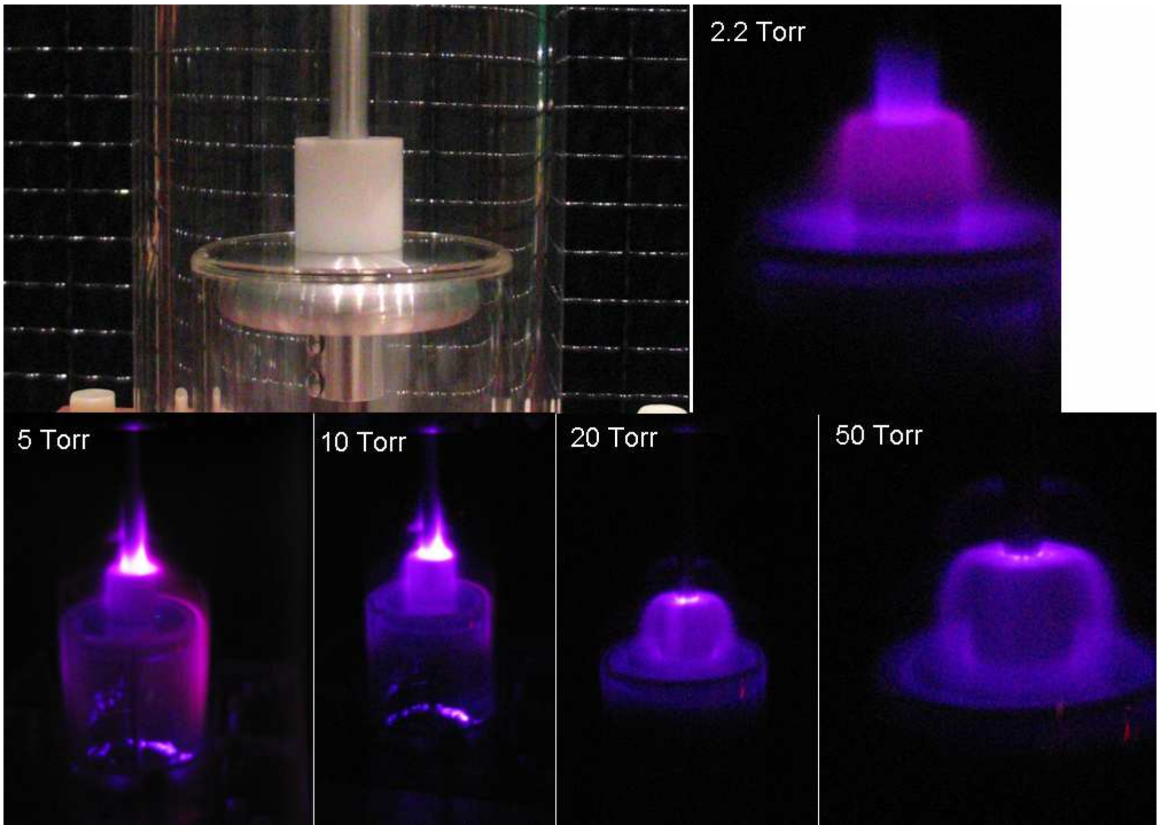


**Figure 3. Visible PD for varying pressure (Teflon insert experiment) [8].**

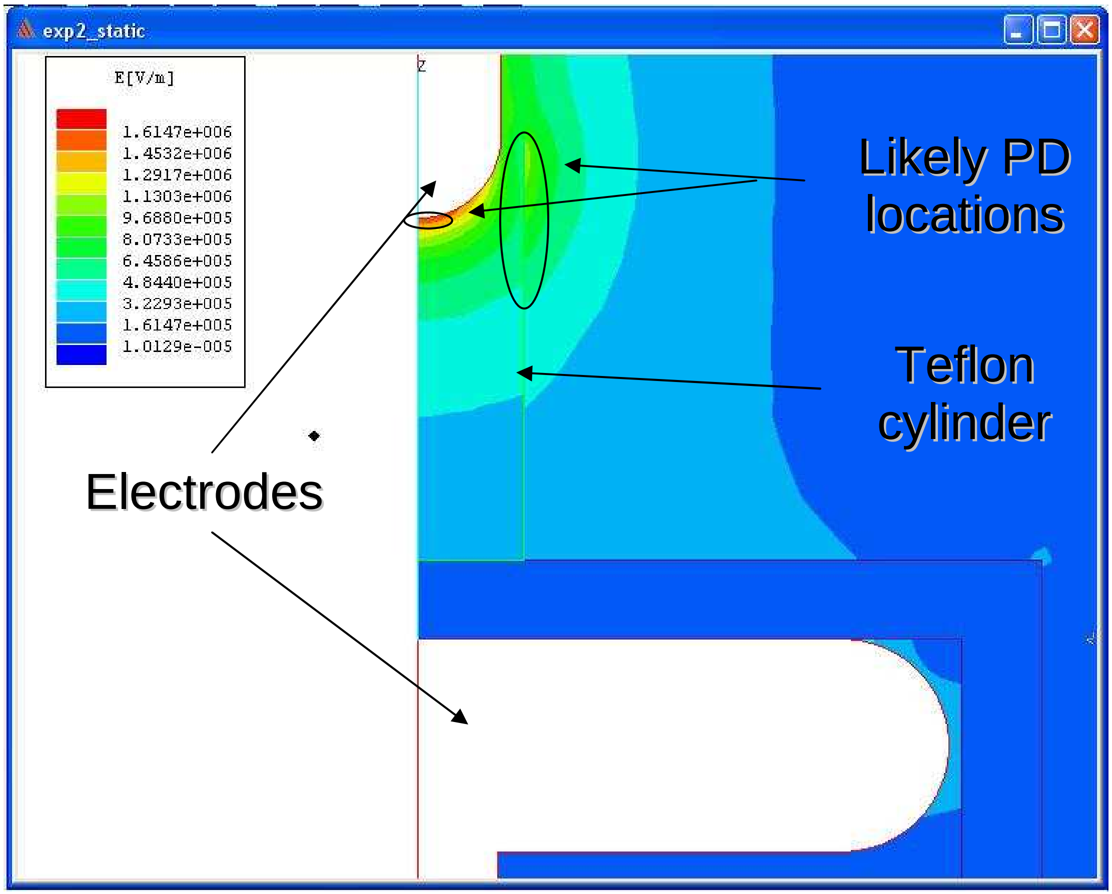


**Figure 4. Maxwell simulation of electric field strength for Teflon insert.**

Figure 5 shows the continuous PD glow for the needle-plane (#1) experiment at various pressures. The visible PD was observed to congregate around the tip and sides of the needle and somewhat along the surface of the lower insulation barrier (particularly at a pressure of 2 Torr).

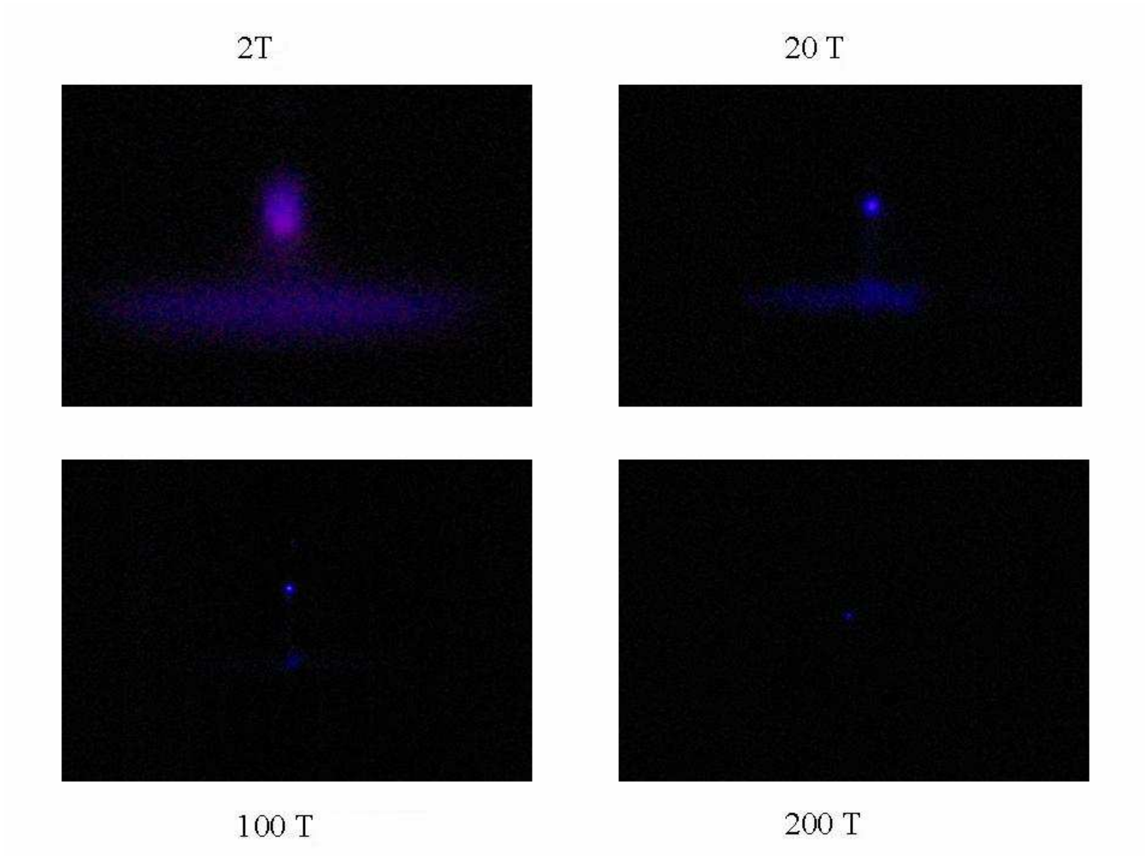


**Figure 5. Visual PD for needle-plane experiment.**

Viewing Figure 6, we see that the electric field strength is indeed highly concentrated around the tip and sides of the needle, but there does not appear to be a relatively high electric field strength on the upper part of the inverted cup barrier.

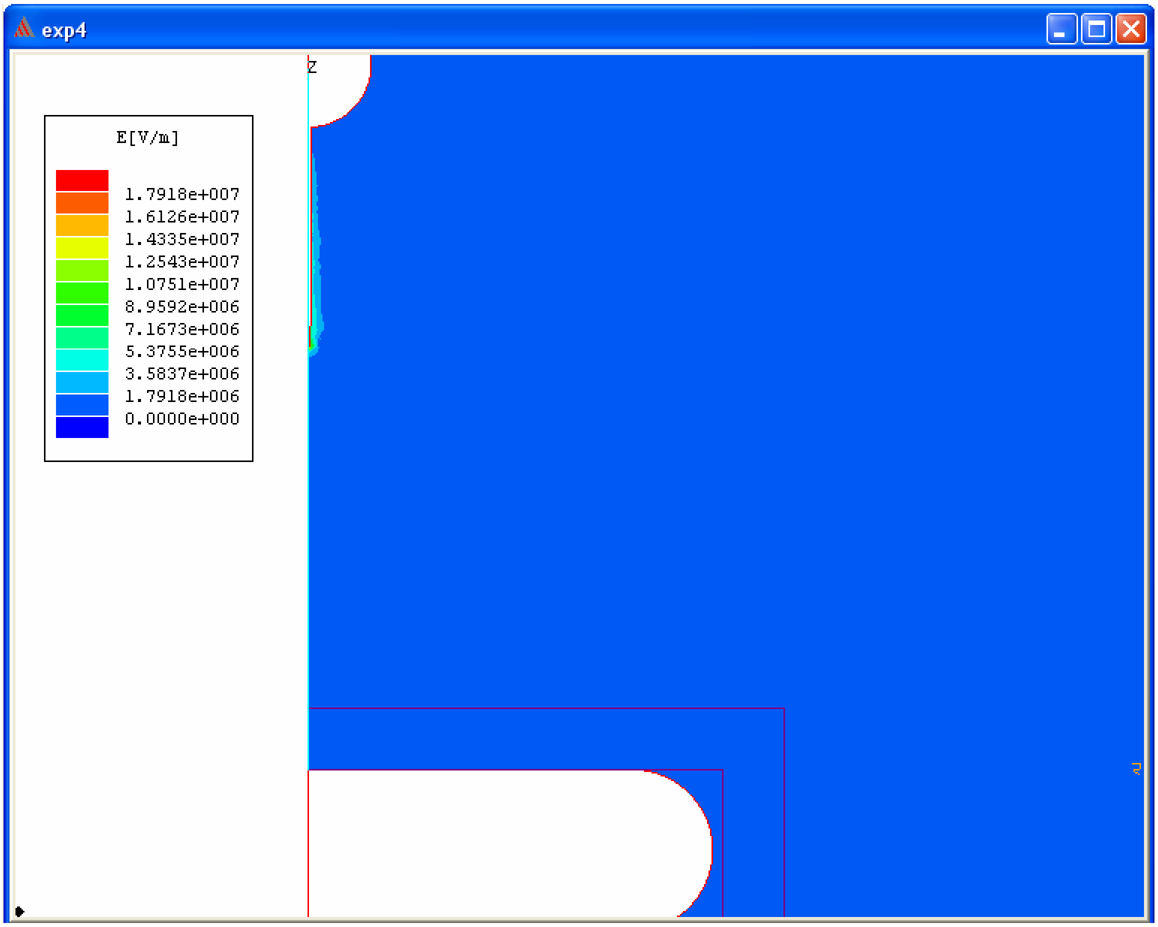


**Figure 6: Electric field strength graph for needle-plane experiment (#1).**

After seeing this discrepancy, a line plot of the electric field strength was created using the data points along the interface between the air and the top of the barrier. Figure 7 shows the results and it can be seen that an electric field strength distribution is present, but not seemingly large enough to account for partial discharge glow that was observed.

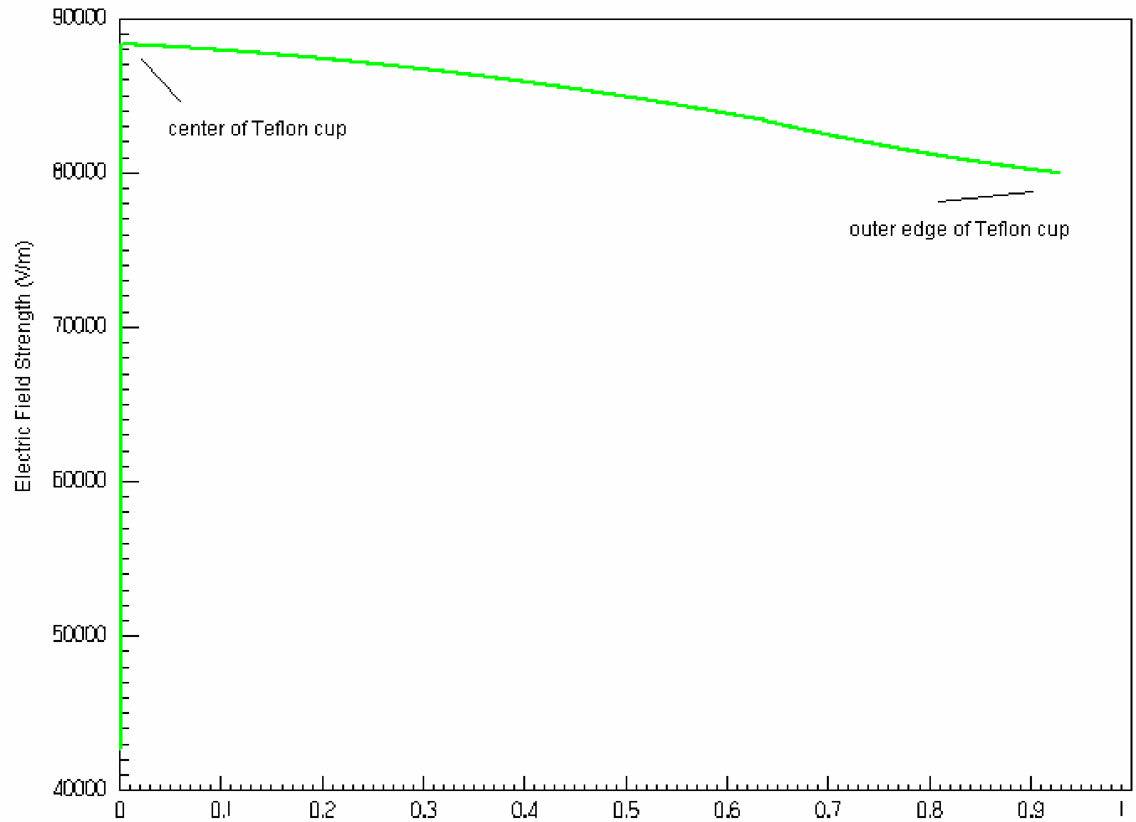


**Figure 7: Electric field strength along barrier interface for Exp #1.**

A concept that is postulated to cause this discrepancy may come from the polarity effect for electrical discharges. The polarity effect usually occurs when an electrode with sharp point(s) is paired with a plane electrode, precisely the case with the needle-plane arrangement in this experiment. Figure 8 illustrates how the difference in applied voltage polarity affects the location of space charge in between two electrodes. An excess of space charge can contribute to a sparkover at an earlier voltage than without the space charge since the collection of charges increases the electric field strength at the point of their location.

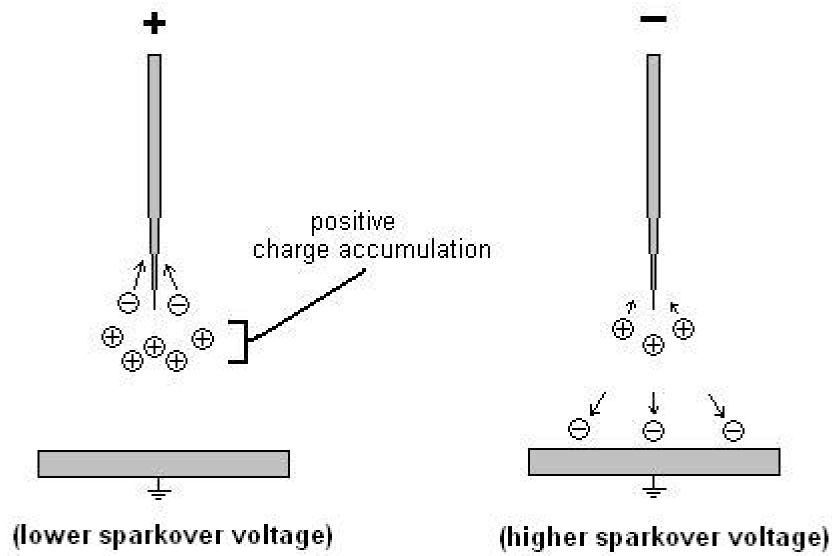


**Figure 8: Space charge comparison for different electrode polarities [4].**

So, for this case, it appears that a negative space charge might be accumulating along the barrier near the plane electrode and contributing to the PD located there. The fact that Maxwell cannot simulate this complicated effect in ionized gases is one drawback in using it for PD location prediction.

Figure 9 shows the Maxwell electric field strength graph for the glass disk experiment (#3). In the lab, PD was only observed along the outer edge of the top electrode, near the interface between the electrode and the glass disk. This is consistent with predictions made from the simulation data. A very large relative electric field strength is noted in an enlarged portion of Figure 9.

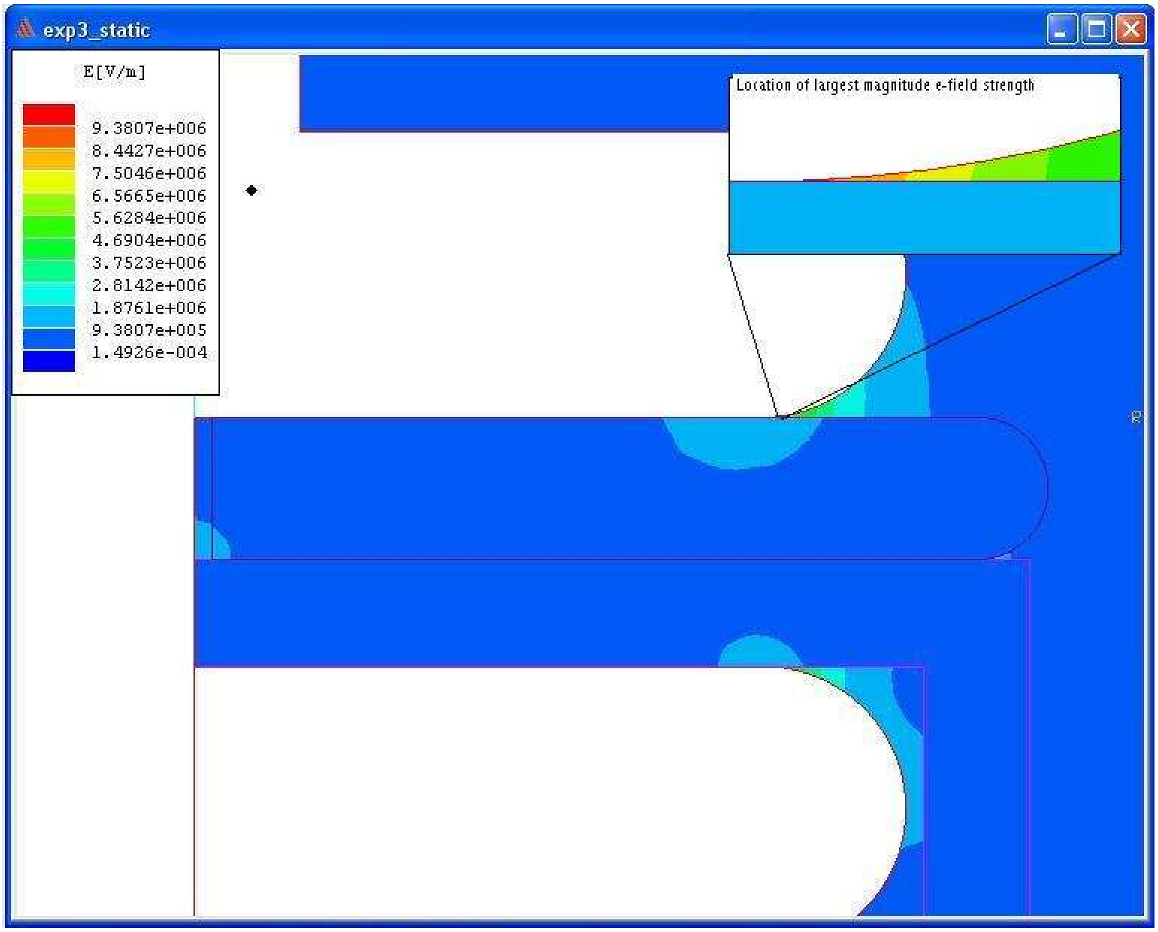


**Figure 9: Electric field strength for glass disk experiment (#3).**

Originally, the glass disk was made for OSU's high voltage laboratory since it was believed that the drilled hole at the center would focus the location of the partial discharges. Both experimental observation and Maxwell simulations seem to show otherwise. This is one advantage to using software such as Maxwell to predict PD location; one can better design experiments without buying any parts or actually spending the time repeating several different experiments until satisfactory results are found.

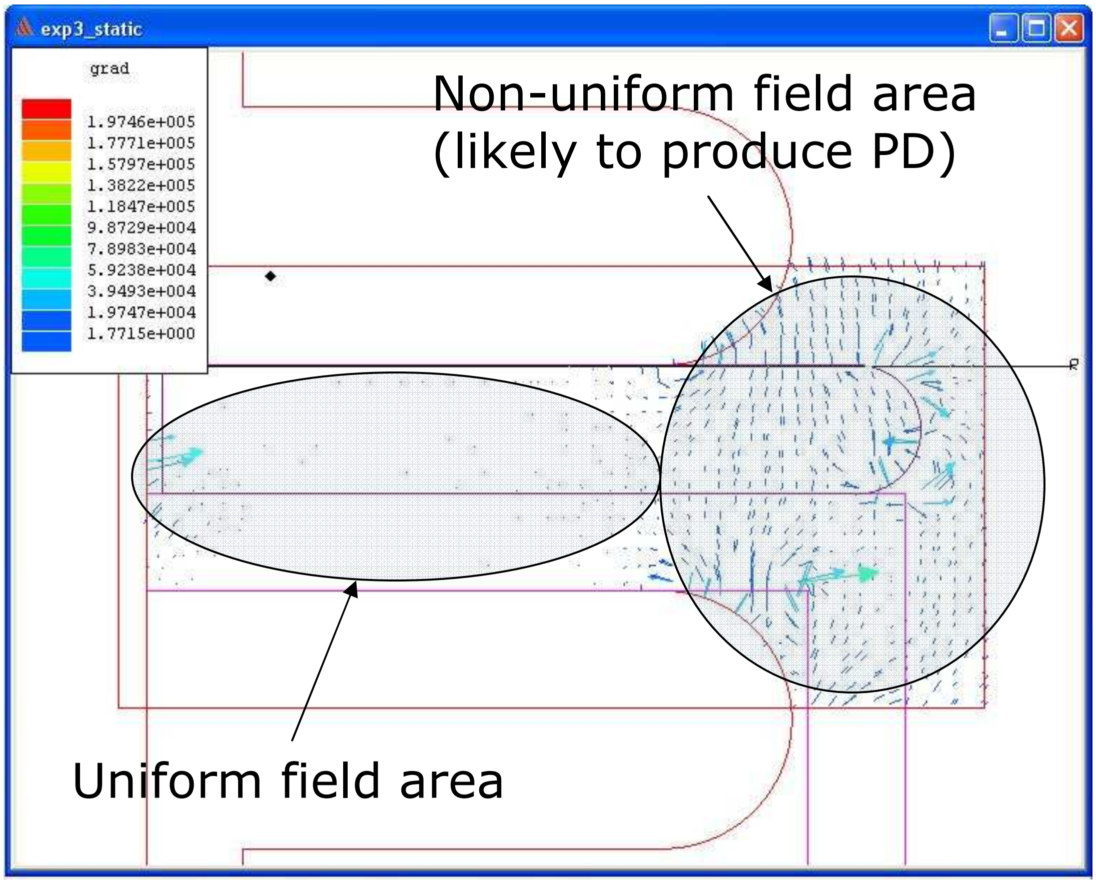


**Figure 10. Gradient of E-field vector angle for glass disk experiment.**

Figure 10 shows the results of post processing applied to the calculated electric field vector quantities stored by the Maxwell program for the glass disk experiment. Combining Maxwell's calculator and plotting feature, the gradient of the vector angle was taken on all electric field vector quantities. Essentially, this operation shows the rate of change of the angle that the electric field vectors make with the horizontal axis. Thus, this operator shows a quantifiable indicator of non-uniformity in the simulated electric field. Where one finds electric field vectors running parallel, this operator is zero. Where the vectors are rapidly changing directions, this operator is large.

The electric field strength has primarily been discussed thus far, but the directional uniformity of the electric field also plays a slight role in partial discharges. Uniform fields generally produce a full sparkover between electrodes while non-uniform fields produce partial discharges until full sparkover is reached at higher voltages [9]. When first conducting research for this project, the author first hypothesized that a relationship existed between the non-uniformity of the electric field and the partial discharge inception voltage. Apparently, though this assertion is not true according to the findings in [10]. According to these findings, a critical electric field strength for PD inception depended on the surrounding gas medium, but independent of electric field non-uniformity. Thus, PD is essentially a more localized version of sparkover phenomenon.

**2.3) Limitations**

Despite the observed accuracy in predicting PD location in controlled laboratory experiments, there are inherent limitations that can be foreseen in using FEM-based software for predicting PD location in less-than-optimal environments. For example, cracks and other deformities in aging insulation change the properties of not only the insulation, but also any insulation-conductor or insulation-to-insulation interfaces, forming small voids where PD can occur [7].

Including these small voids in a Maxwell model can greatly affect the simulation results. Not only are large differences in apparent electric field strength observed, but also there is a troublesome issue inherent to most FEM based software to deal with. When generating a field solution, Maxwell refines elements of the solution until an acceptable tolerance is met. When small cracks or voids are introduced into a Maxwell model, it can take much trial and error effort to get the software to converge with acceptable accuracy. The trial and error comes from refining an initial "mesh" for the software. The initial mesh is simply the collection of the starting elements that Maxwell solves on the first iteration. Further iterations solve finer meshes of elements until an accurate solution is achieved. When refining the initial element mesh to converge on small pieces of the model geometry (such as small voids/cracks), one has to do one of two things:

1) Accept an approximate shape for the troublesome piece of geometry. Simpler shapes tend to yield solutions that converge.
2) Edit the Maxwell's initial mesh to include many small elements within the small geometry. This gives the software a better starting point and thus a better chance for converging on usable solution.

### 2.4) Summary

In conclusion of this set of tests, it appears that electromagnetic field solver software packages such as Maxwell can indeed predict the location of partial discharges fairly accurately for PD experiments done in the laboratory. Within the software's graphical solution for the electric field strength, locate areas of high magnitude relative to other areas within the experiment. It must be noted though, that Maxwell has not been put to the test in the field where practical issues such as aging and other forms of damage to insulation or other parts of equipment can alter the location of PD. Also, Maxwell has limitations when trying to simulate common aging defects such as cracks and voids. Nevertheless, it appears that software can help laboratory scientists and engineers visualize and design partial discharge experiments that exhibit PD in a certain location.

# Chapter 3

## (3) Comparison of Partial Discharge Detection Equipment Used

### 3.1) Reasoning Behind Experiment

In order to verify that both PD detecting devices used in the OSU high voltage laboratory did indeed produce equivalent results, it was decided to perform the same PD detection experiment (needle-plane electrodes with Teflon cup barrier). All of the other tests done in the high voltage lab for this research project used the computer for detecting PD onset. The reasoning for comparing the computer to the oscilloscope is because the computer unit is a new piece of equipment recently developed by Innovative Scientific Solutions Inc. and given to the OSU high voltage lab. To ensure that the computer gives reasonable inception voltage results, a comparison to the well-tested oscilloscope was thought to be in order.

### 3.2) Results

Both the high voltage lab's oscilloscope and PD detection computer were used to determine the partial discharge inception voltage for a set range of pressures within the test chamber for the needle-plane electrode experiment.

The following table shows the collected data along with a column for the magnitude difference between the two devices.

| | Inception Voltage | | |
|---|---|---|---|
| Pressure (Torr) | w/ oscilloscope (V) | w/ computer (V) | Magnitude Difference |
| 2.2 | 514 | 521 | 7 |
| 5 | 610 | 600 | 10 |
| 10 | 733 | 717 | 16 |
| 20 | 800 | 796 (830) | 4 (30) |
| 50 | 1250 | 1156 (1130) | 94 (120) |
| 100 | 1570 | 1771 (1384) | 201 (186) |
| 200 | 2500 | 2500 – 3100 | 0 – 600 |
| 760 | 4840 | N/A | N/A |

**Table 1: Inception voltage data comparison between oscilloscope and PD detection computer.**

The data in parentheses in the "w/computer" column indicates a point where the measured inception voltage was appreciably different when measured a second time. The difference in results is believed to have come about when attempting to define the line where continuous PD (approximately one PD event per cycle of the applied 60Hz AC voltage). Also, according to [11] the variability in partial discharge inception voltage measurements can also come from the amount of time applied voltage is maintained on the experimental apparatus and local temperature changes.

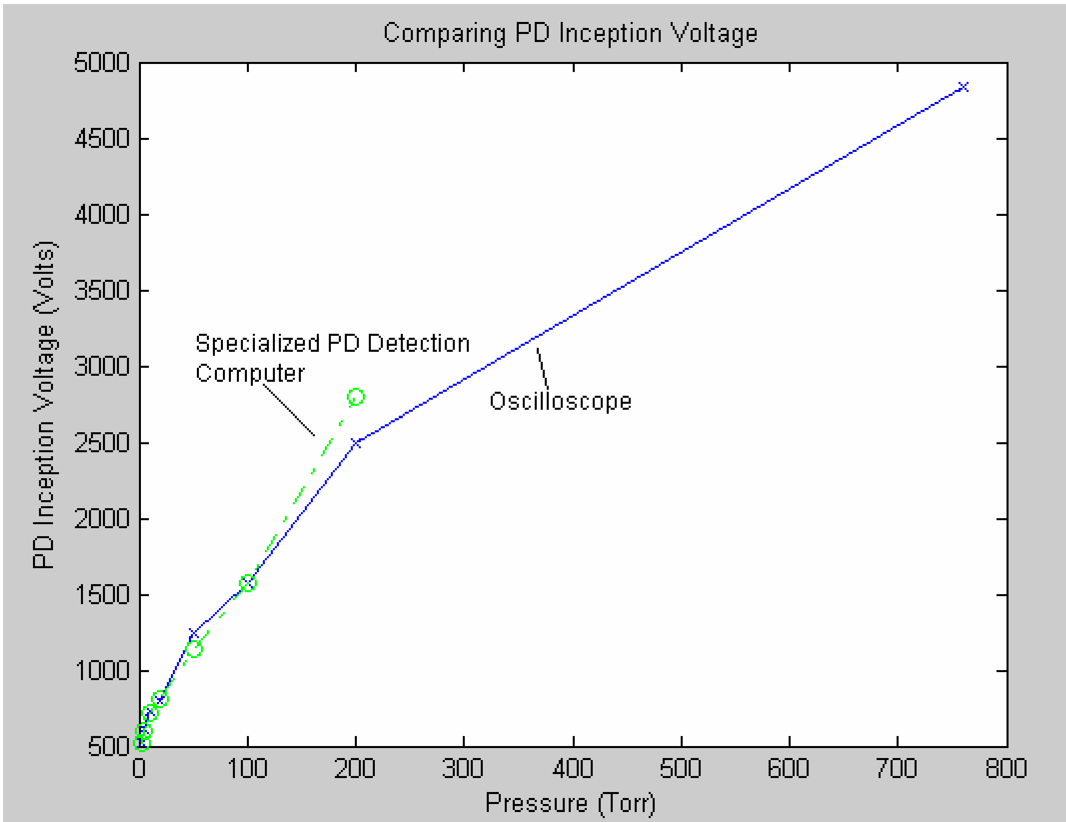


**Figure 11. Plots of data from needle-plane experiments.**

The contents of Table 1 are plotted in the graph above. If two inception voltage data points were measured for a particular pressure, the average was taken and used for the purposes of plotting. Note that no data point was taken at 760 Torr for the computer's curve. No data point was measured since the applied voltage was approaching very close to an imposed voltage limit at around 5kV. Damage to the test chamber was to be avoided if a full sparkover or flashover were to occur.

### 3.3) Summary

So, to sum up the results from this chapter, the oscilloscope and the PD detection computer system seem to agree well for lower pressures (lower inception voltages) in the case of this particular experiment. The occurrences when trying to measure inception voltage at 200 Torr seems to be the only datum that fell out of an acceptable range, but the data collected at that time was fluctuating somewhat. Overall, the new partial discharge detection computer used in the high voltage lab appears to work fairly well for measuring precise counts of PD incidents as long as the trigger settings are properly set.

## Chapter 4

## (4) PD Inception Voltage Measurements and Results

### 4.1) Data Collection Technique

The primary data collection device used for nearly all PD inception voltage experiments was the PD detection computer. The technique for obtaining this data on the computer was to slowly raise the applied voltage when close to the expected PD onset voltage. When the computer registered some partial discharge incidents, the voltage was backed off until no more incidents were registered. Then, the applied voltage was raised very slowly until approximately 60 PD incidents per second were registering on the computer consistently.

### 4.2) Results

Figure 12 below shows the results of the PD inception voltage tests performed on the three experimental configurations studied in this research period.

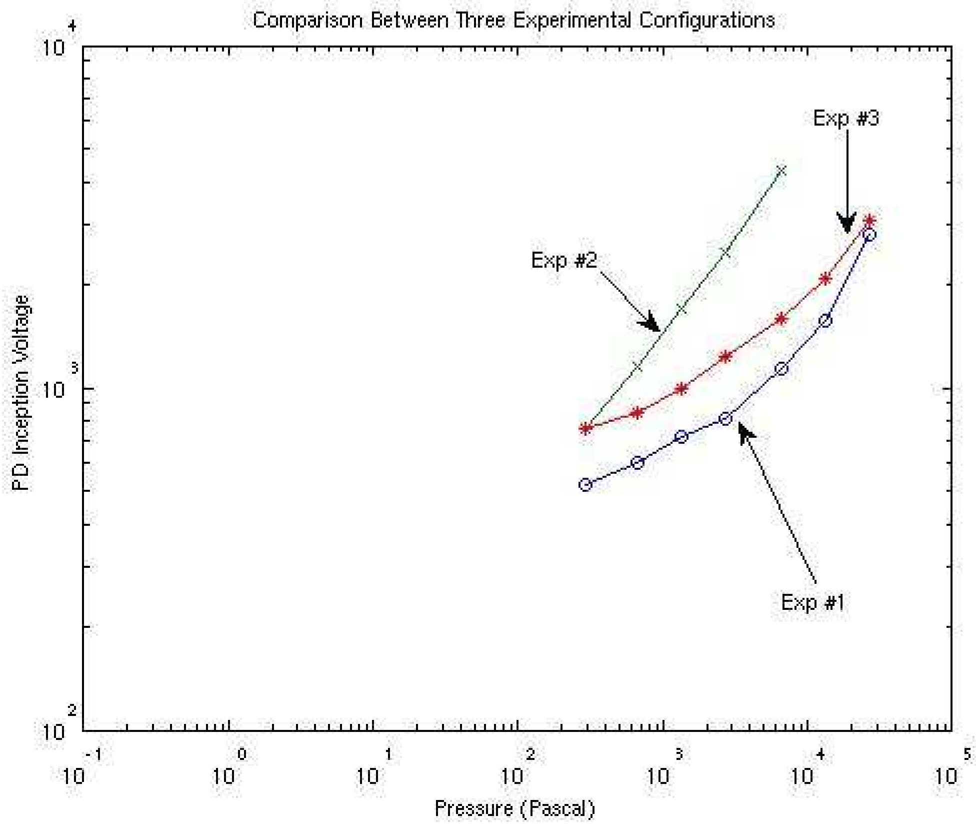


**Figure 12: Recorded PD inception data.**

In order to judge that the PD inception voltage data collected was consistent with other research findings, the data was plotted on a similar scale to the data in Figure 13 and compared. While the data in Figure 13 is for helium and argon gases, the shape of the curves follows a well known set of curves loosely labeled “Paschen-like” PD inception voltage curves. Incidentally, [10] shows that their curves also closely resemble the Paschen curve for sparkover inception voltage. In any case, the recorded data from the high voltage laboratory follows the same general trend as the right half data points in

Figure 13.  As a rule, the pressure chamber at OSU's high voltage lab is not to reduce the internal pressure below around 2.3 Torr (307 Pascal).  So, for the equipment available, only the right hand side of the Paschen-like curve could be recorded for each experiment configuration tested.

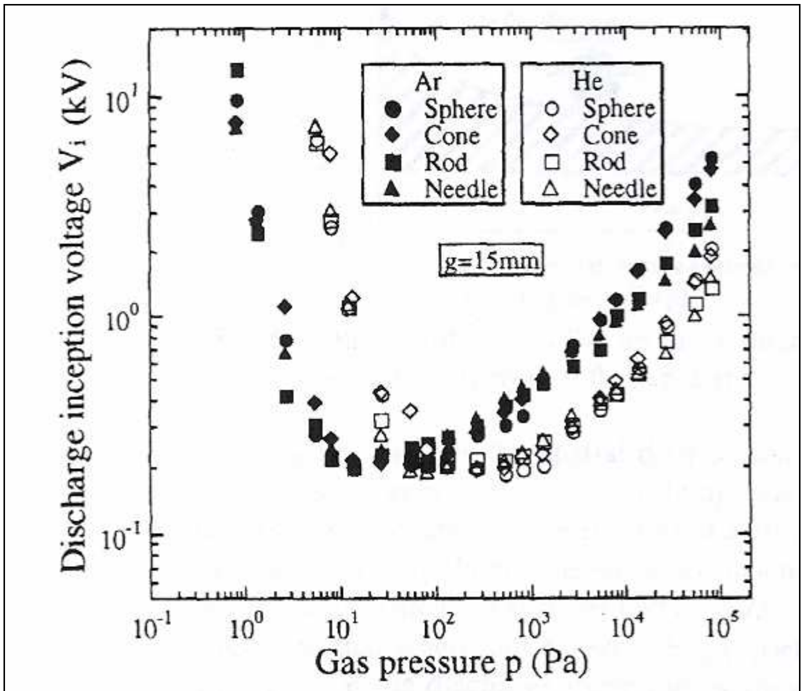


Fig. 2  Discharge inception voltage as a function of gas pressure in He and Ar for different electrode configurations.

**Figure 13:  PD inception voltage data [10].**

## 4.2) Summary

In conclusion, an acceptable amount of inception voltage data points were measured that stayed within the safe applied voltage range for the test chamber equipment. These curves were compared with similar “Paschen-like” curves found in [1, 10] and seem to be reasonably shaped.

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## Appendix

*** See presentation slides used for Denman Undergraduate Research Forum and Thesis Defense for a glimpse at the progression of the research project from its earlier stages (located at Ohio State University Libraries Knowledge Bank.